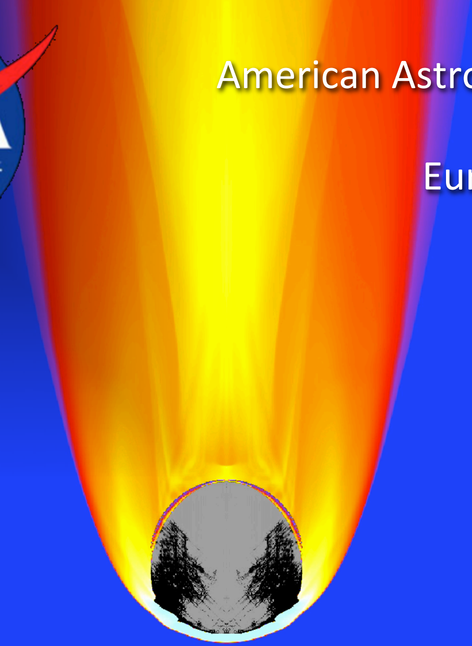
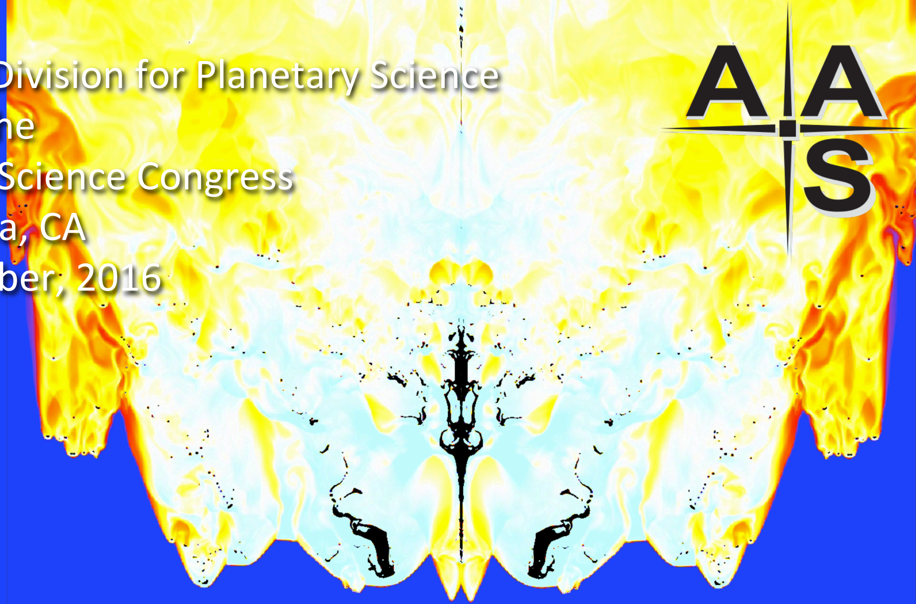
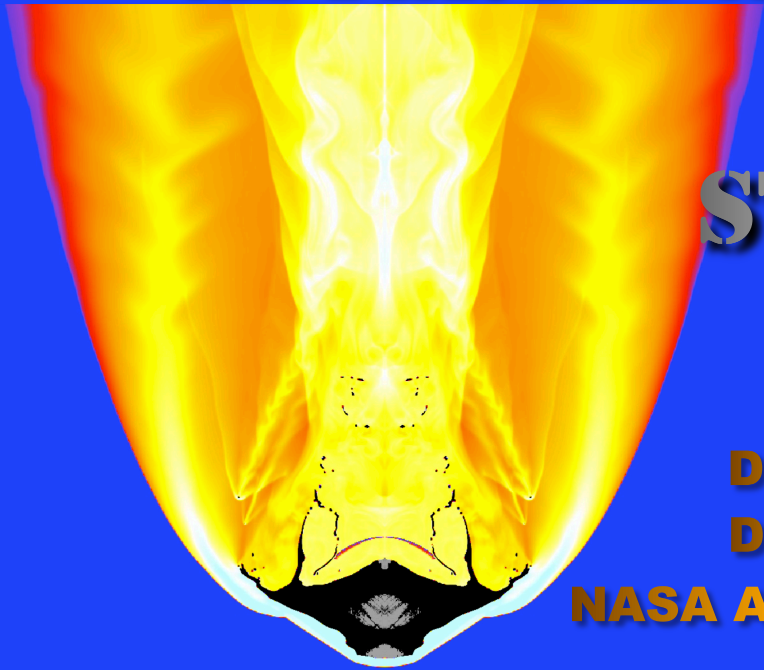
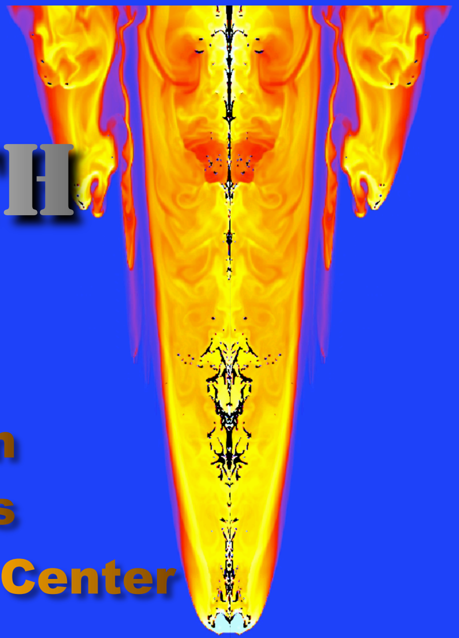




American Astronomical Society Division for Planetary Science
and the
European Planetary Science Congress
Pasadena, CA
16 – 21 October, 2016

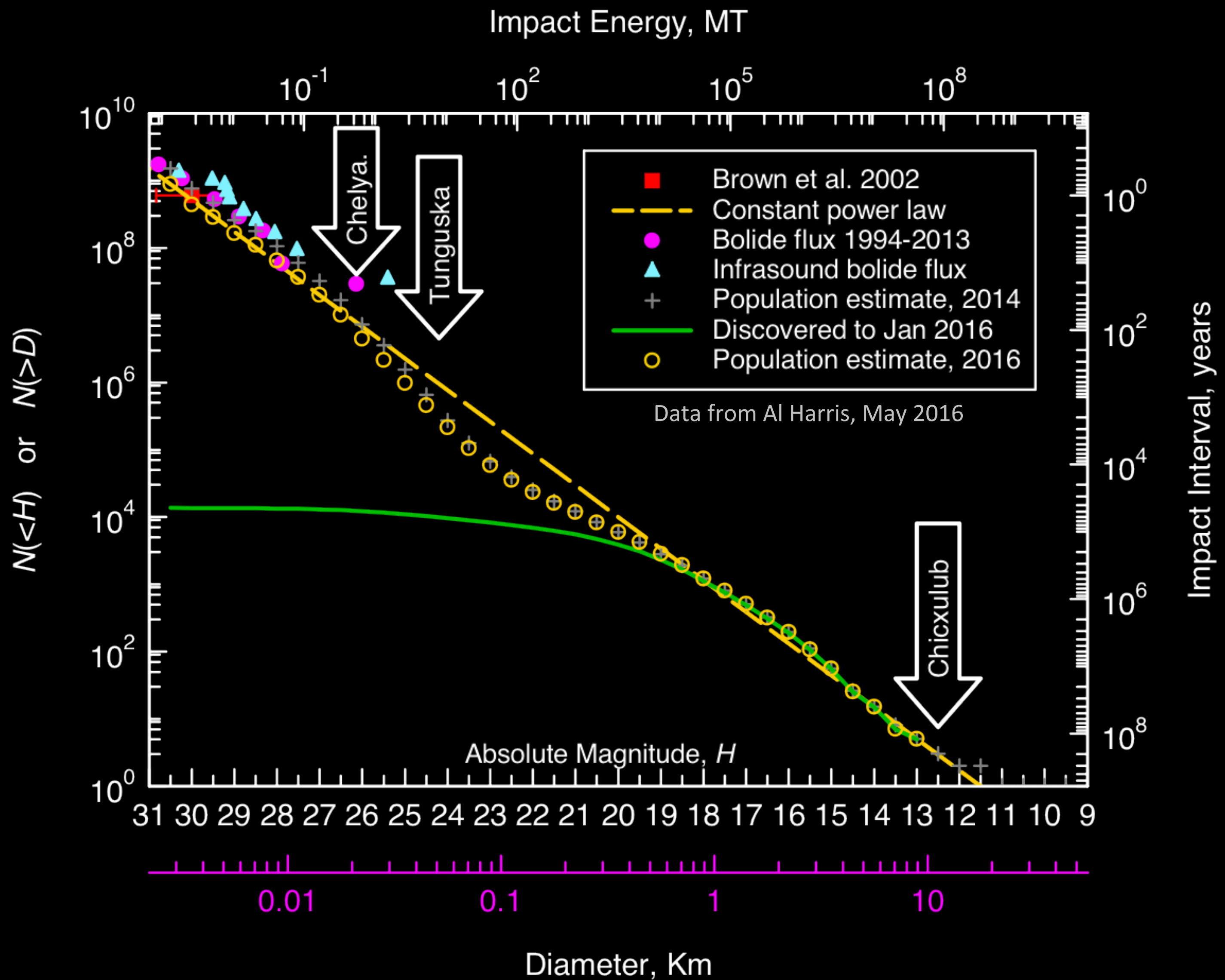
ASTEROID AIRBURST ALTITUDE VS. STRENGTH





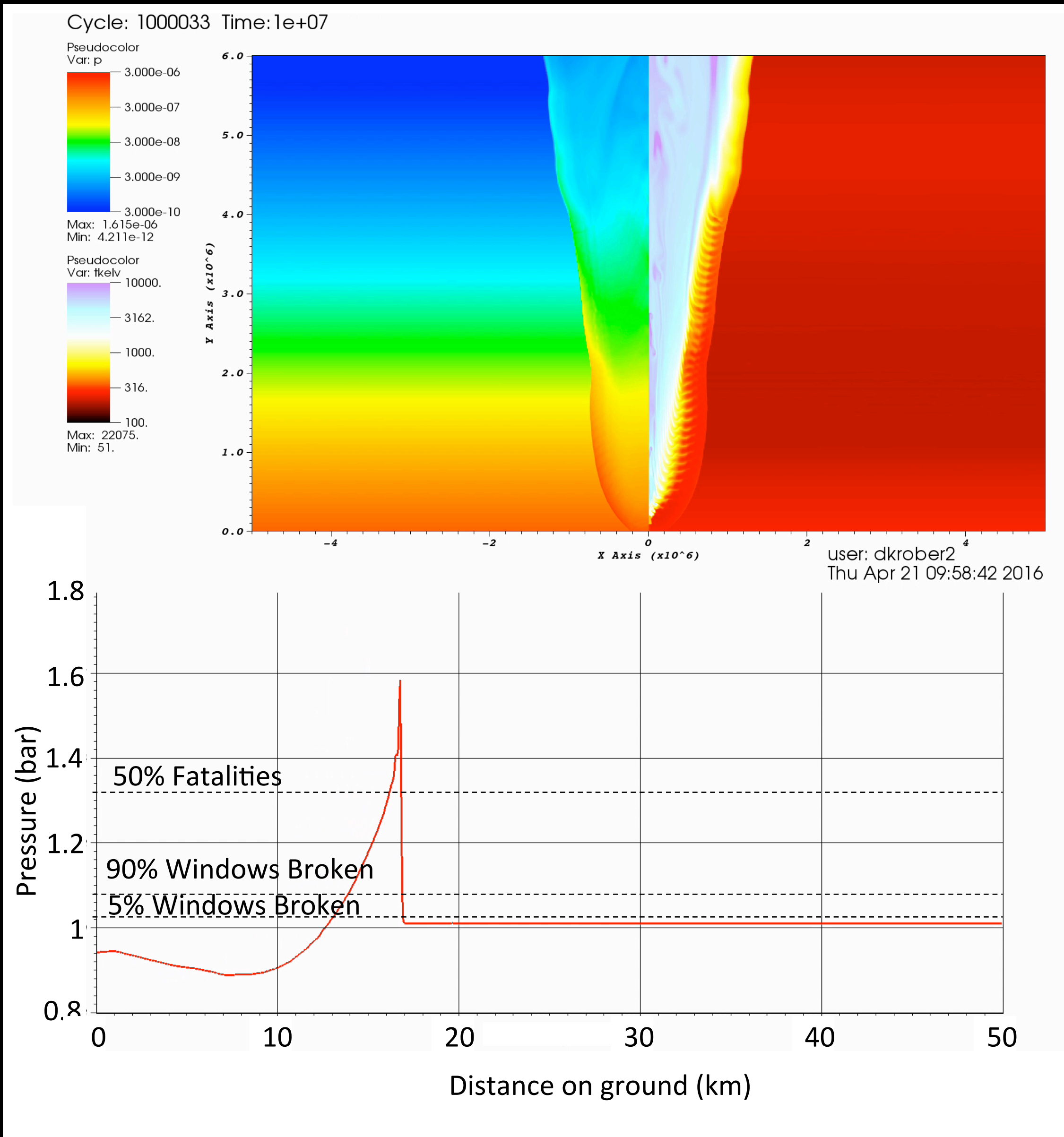
Darrel Robertson
Donovan Mathias
NASA Ames Research Center

Asteroid Populations



Why is airburst altitude important?

- We will be hit by many more “city-killer” size asteroids than “dinosaur-killer” ones.
- Asteroids <100m diameter often burst in the air rather than cratering into the ground/ocean
- A 5MT blast is lethal (50% expected fatalities) out to about 10 km and a 100 MT blast is lethal out to about 30 km line-of-sight.
- The ground damage will be very different if these occur high in the atmosphere versus close to the ground.

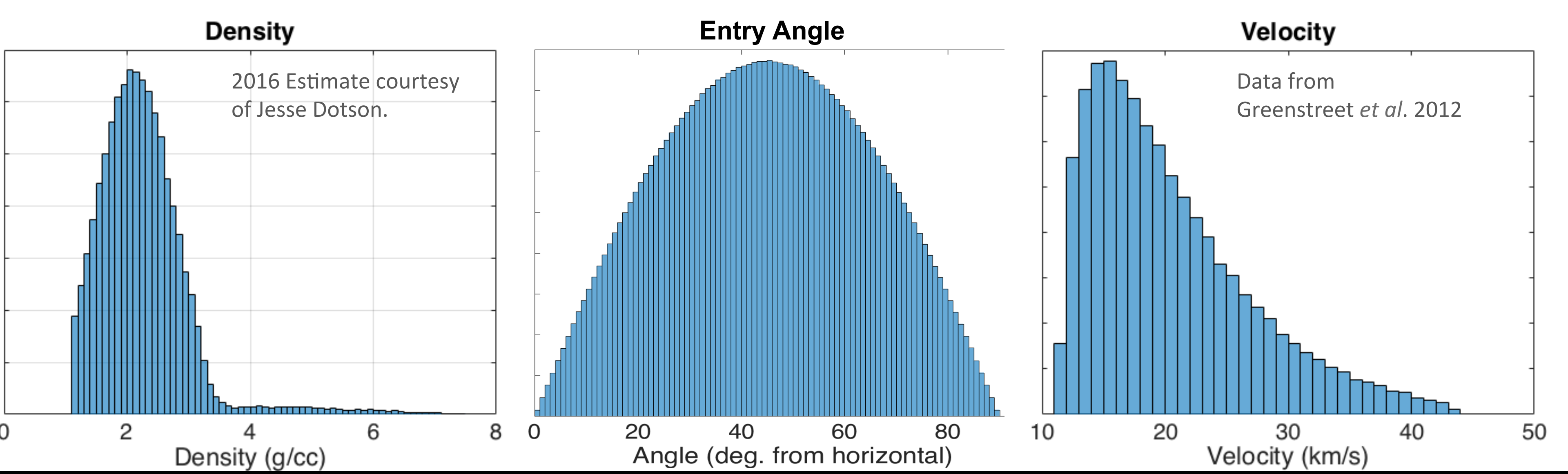


The Problem

- How does the mechanical strength of an asteroid relate to the airburst altitude?
- Meteor strengths inferred from break-up altitudes do not match the measured strengths of meteorites nor inferred cohesive strengths of rubble-pile asteroids
  - Strength inferred from stagnation pressure at burst (~0.1 – 10 MPa) .
  - Meteorite measured strengths (10 – 300 MPa)
  - Rubble-pile asteroid inferred cohesive strengths (10^{-5} – 10^{-3} MPa)

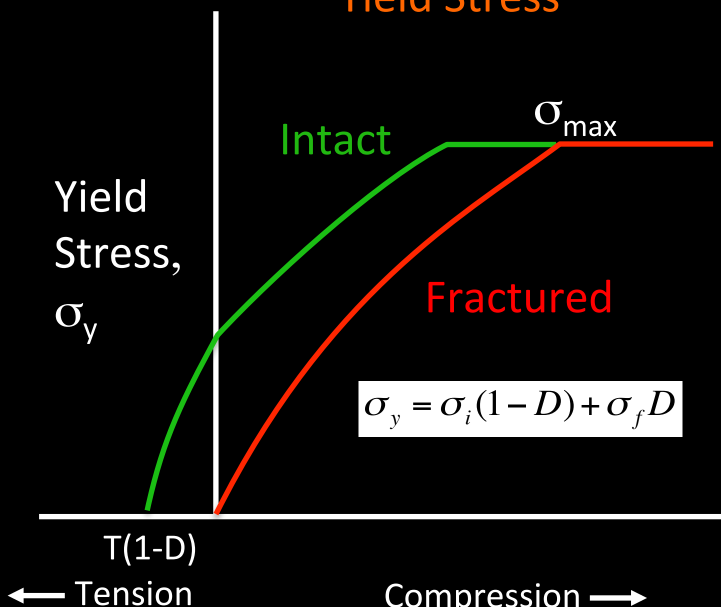
The Solution

- Run a set of hydrocode simulations for different asteroid properties and entry conditions



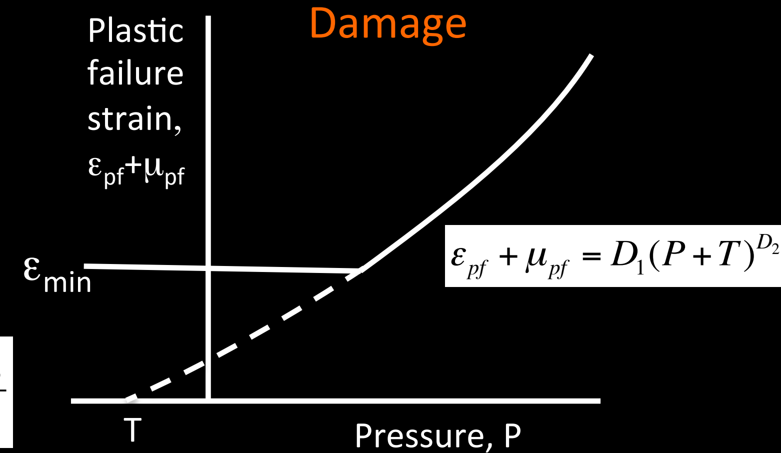
- Strength 0.1, 1, 10 MPa
- Size Ø20, 100m
- Density 1, 2, 4 g/cc
- Entry angle 20, 45, 90°
- Speed 12, 20, 35 km/s

Rock Model

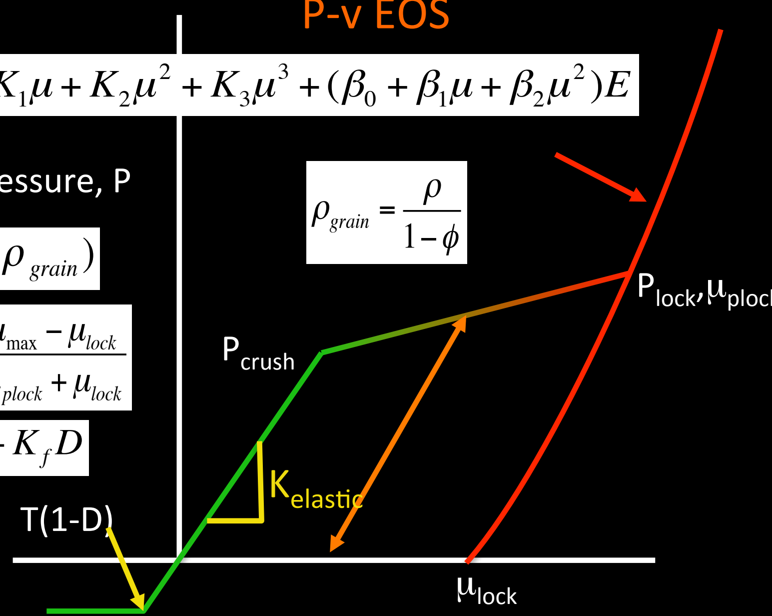


$$\sigma_y = \sigma_i(1-D) + \sigma_f D$$

$$D = \sum \frac{\Delta\varepsilon_p + \Delta\mu_p}{\varepsilon_{pf} + \mu_{pf}}$$



$$\varepsilon_{pf} + \mu_{pf} = D_1(P+T)^{D_2}$$



$$P = K_0 + K_1\mu + K_2\mu^2 + K_3\mu^3 + (\beta_0 + \beta_1\mu + \beta_2\mu^2)E$$

$$\rho_{grain} = \frac{\rho}{1-\phi}$$

$$P = (1-\phi)P_{grain}(\rho_{grain})$$

$$K_f = K_i \frac{\sigma_f}{\sigma_i}$$

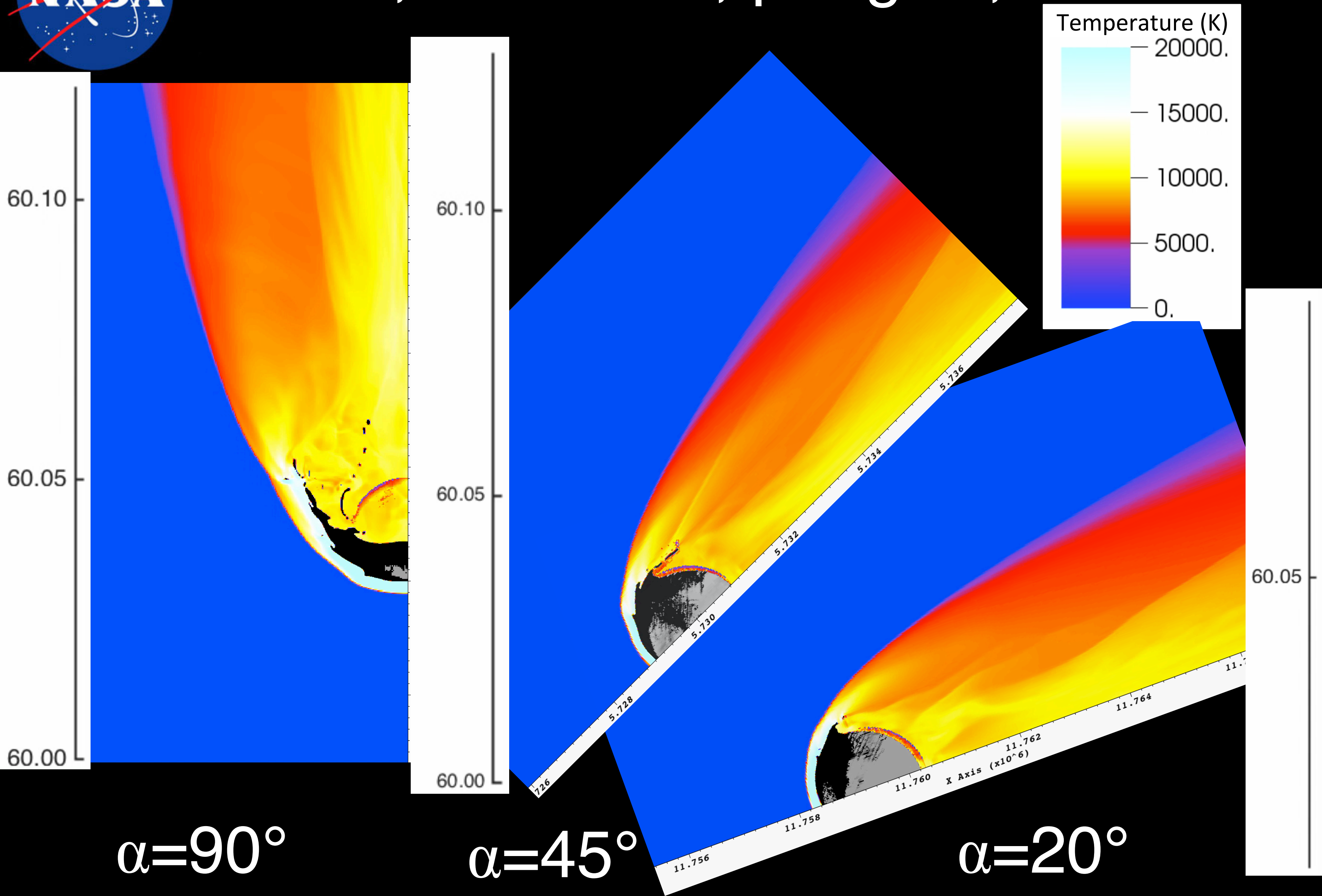
$$F = \frac{\mu_{max} - \mu_{lock}}{\mu_{plock} + \mu_{lock}}$$

$$K = K_i(1-D) + K_f D$$

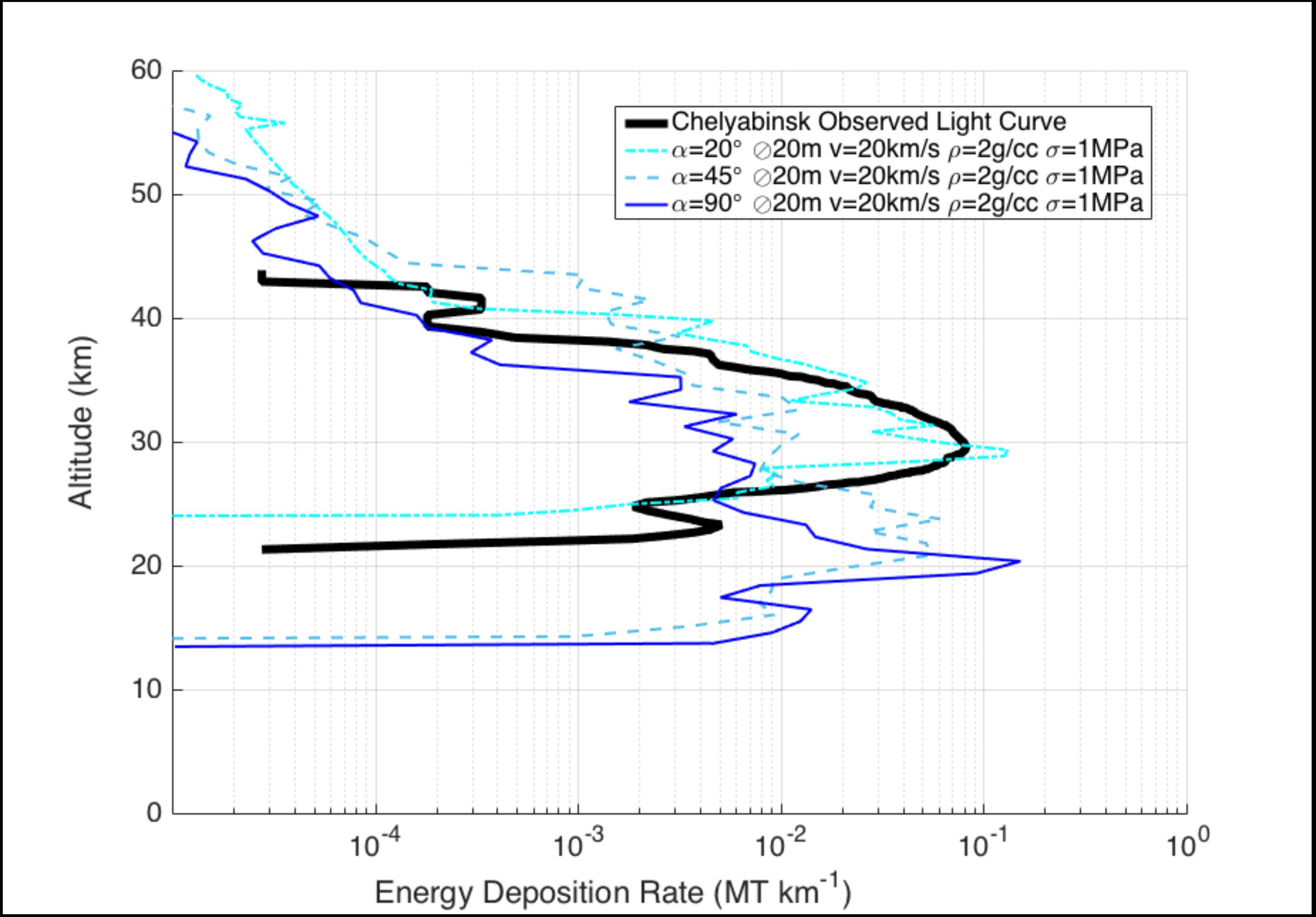
- In these simulations
  - Assume brittle
  - Neglect porosity
  - No melt/vaporization

Triaxial Tensile Yield Pressure, T (MPa)	-0.03	-0.3	-3	-30
Shear Yield Stress (MPa)	0.1	1	10	100
Uniaxial Compression Yield Stress (MPa)	1	10	100	1000

Ø20m, v=20km/s, ρ=2g/cc, σ=1MPa

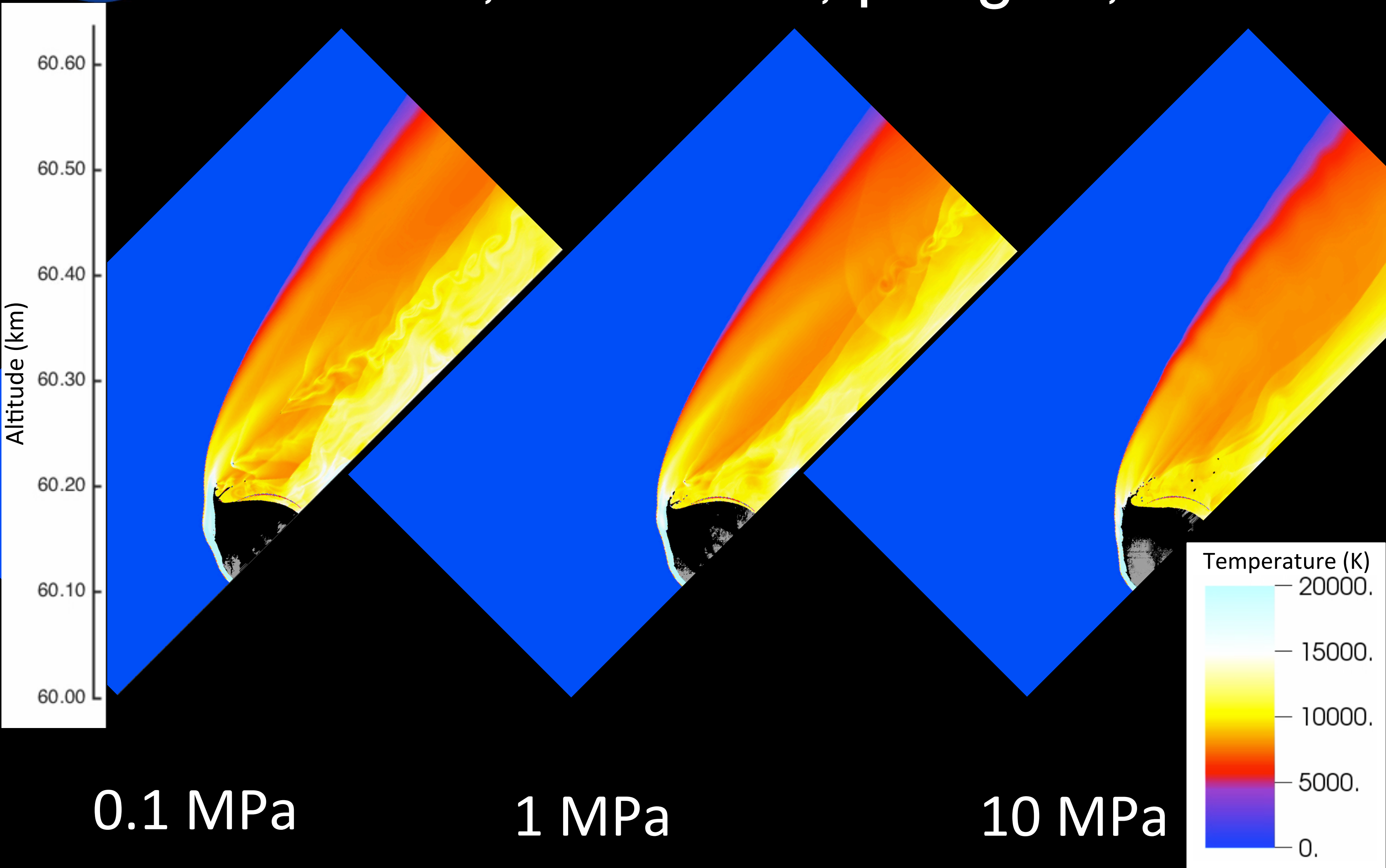


Chelyabinsk-like

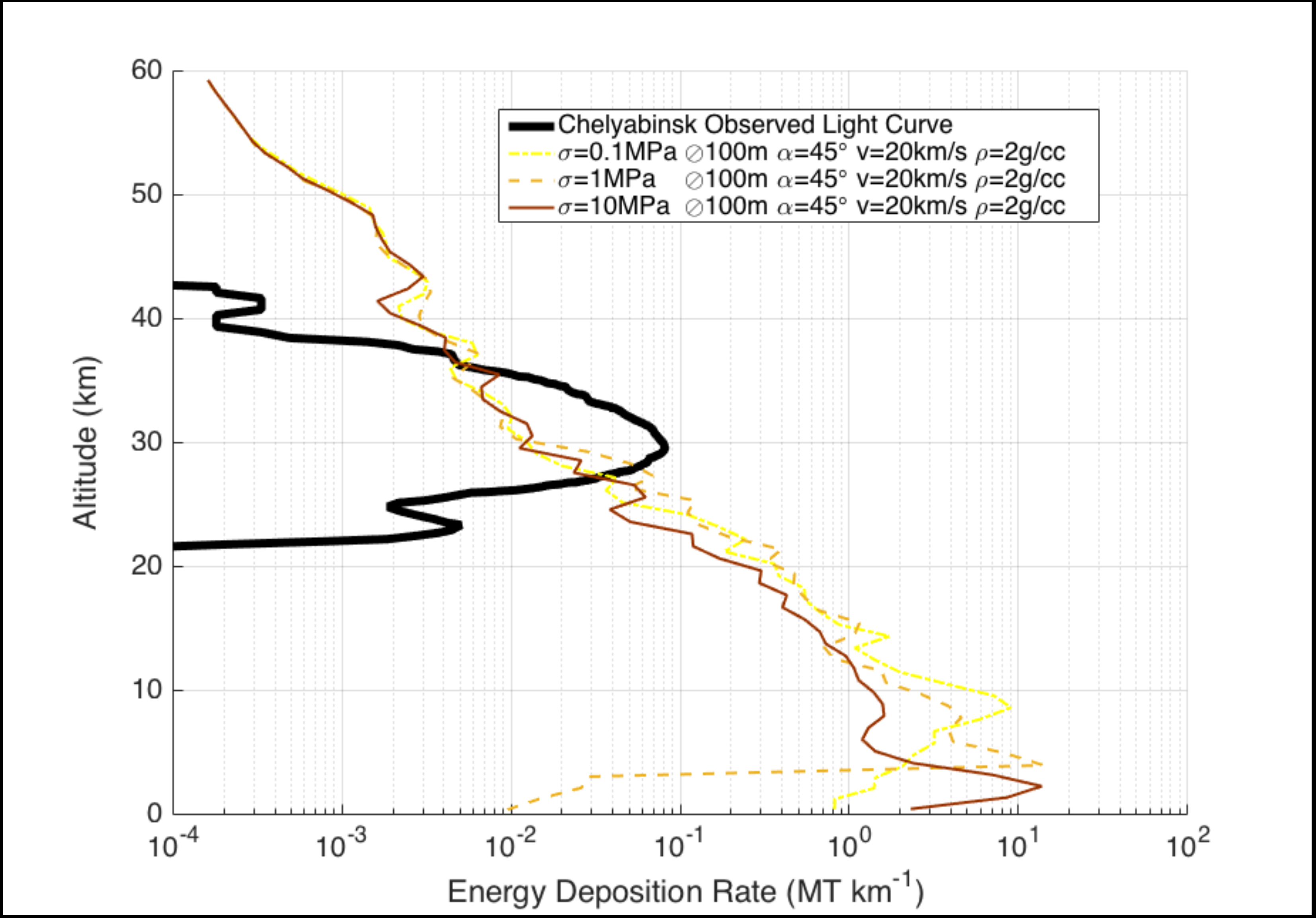


Effect of Strength

Ø100m, v=20km/s, ρ=2g/cc, α=45°

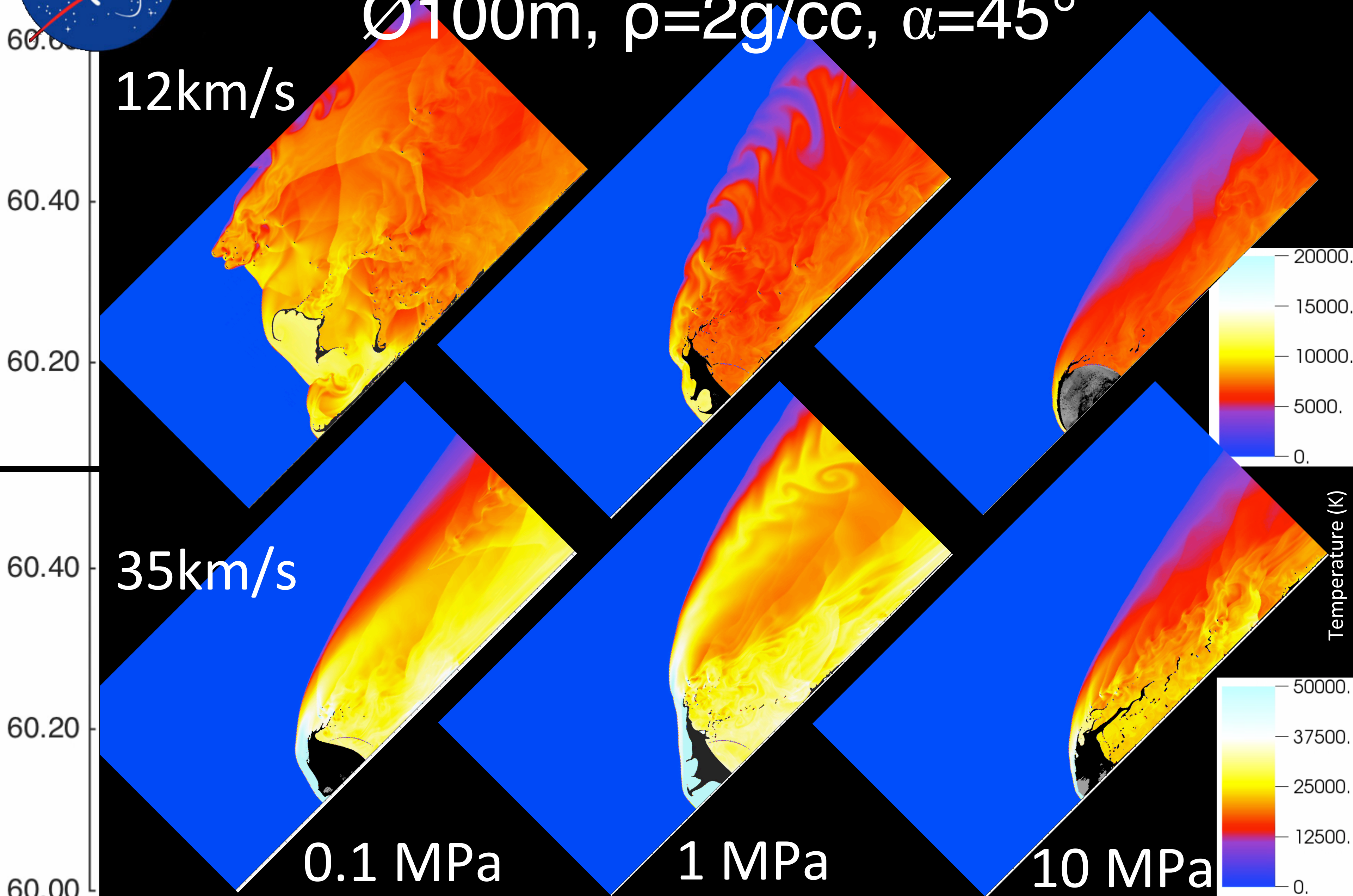


Ø100m, Average Properties

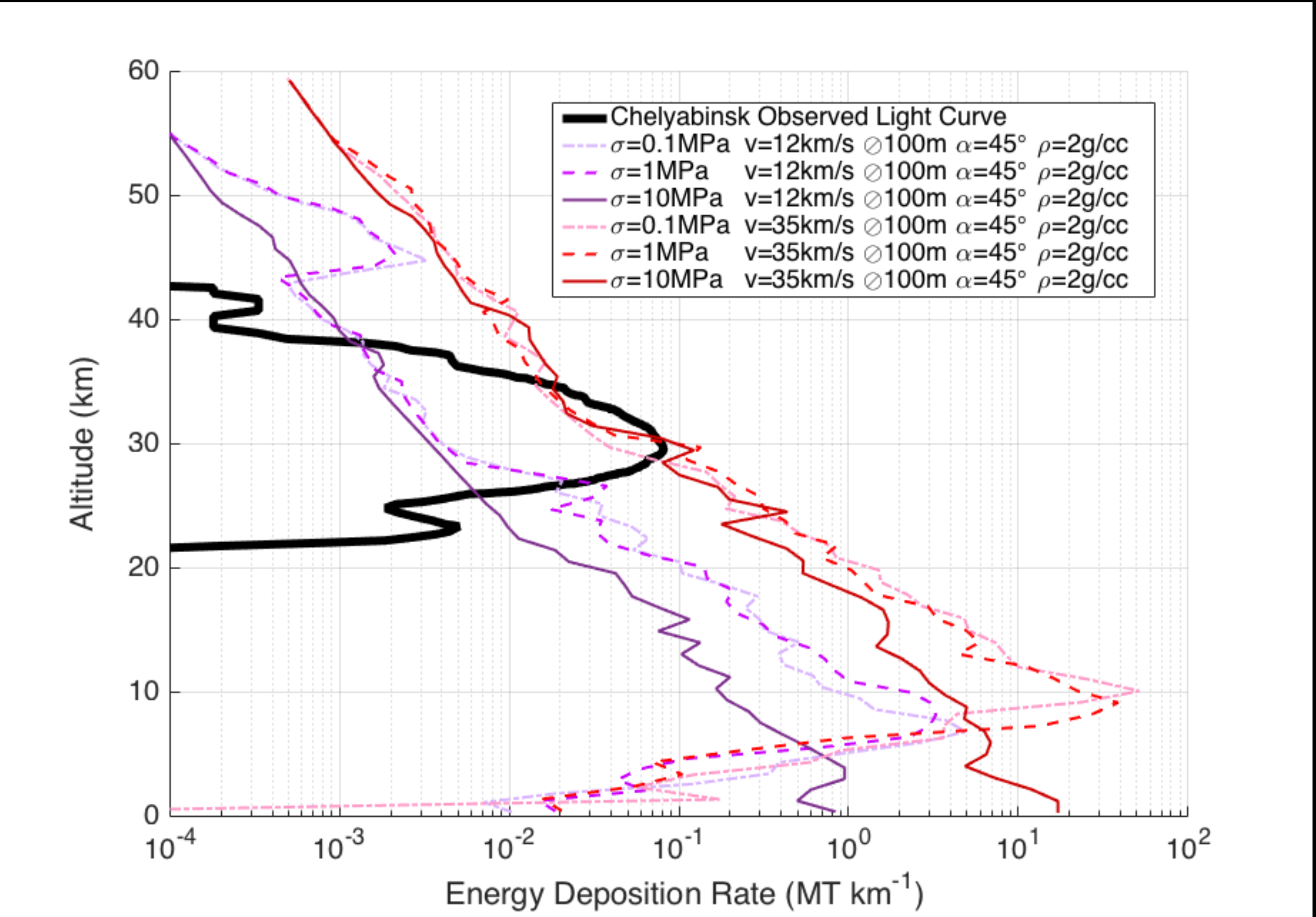


Effect of Speed

Ø100m, ρ=2g/cc, α=45°

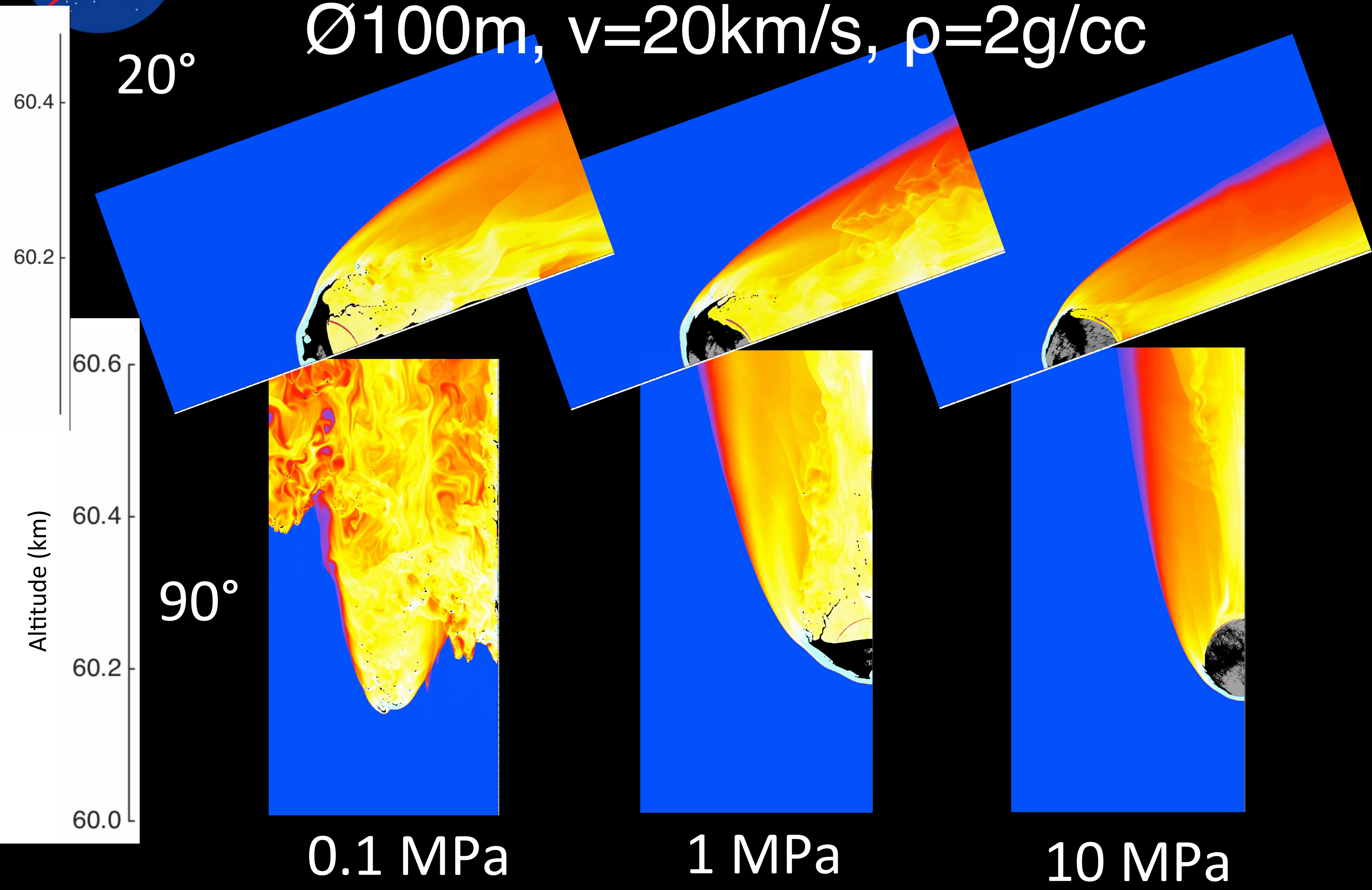


Effect of Speed

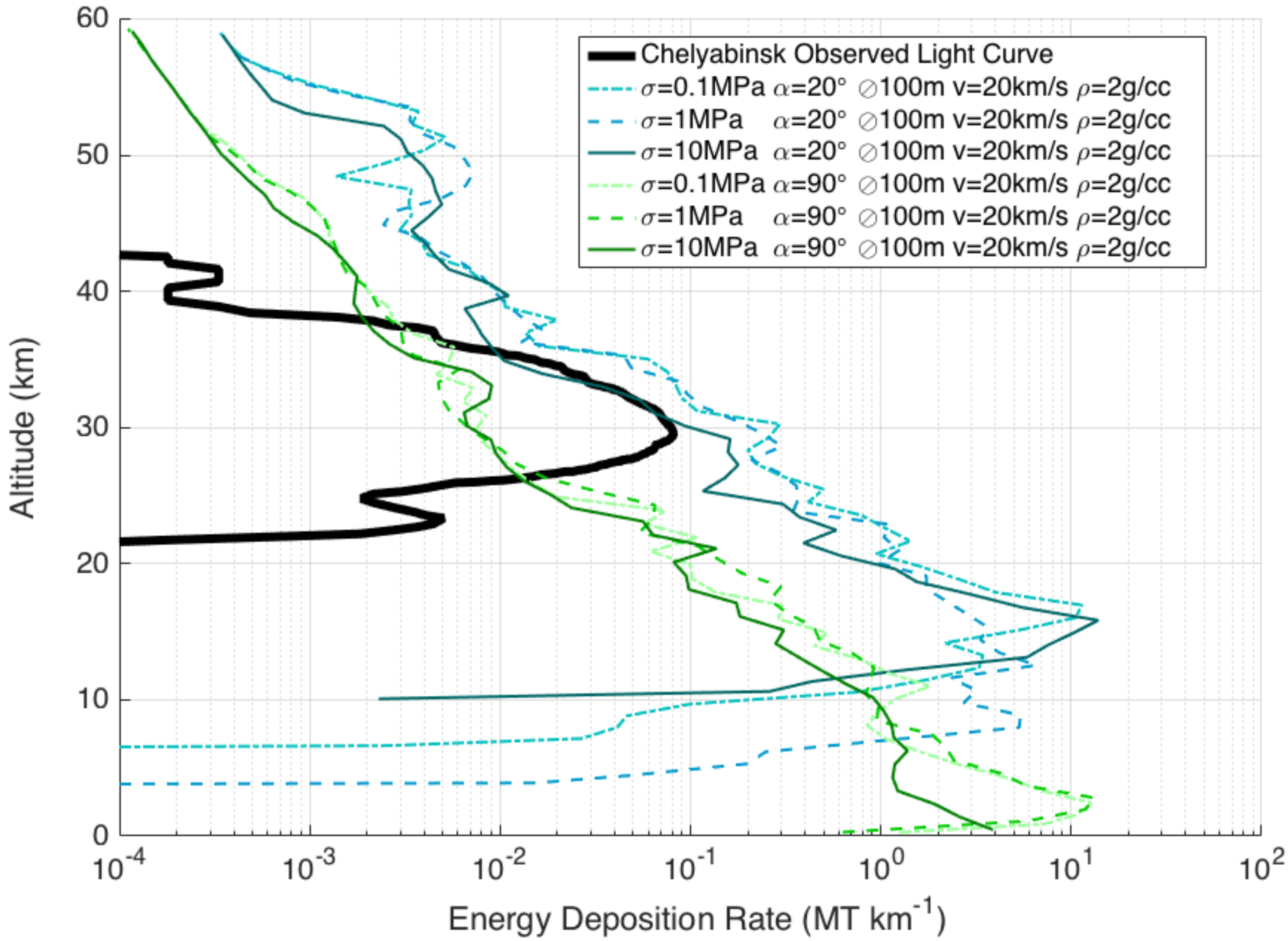


Entry Angle

Ø100m, v=20km/s, ρ=2g/cc



Entry Angle

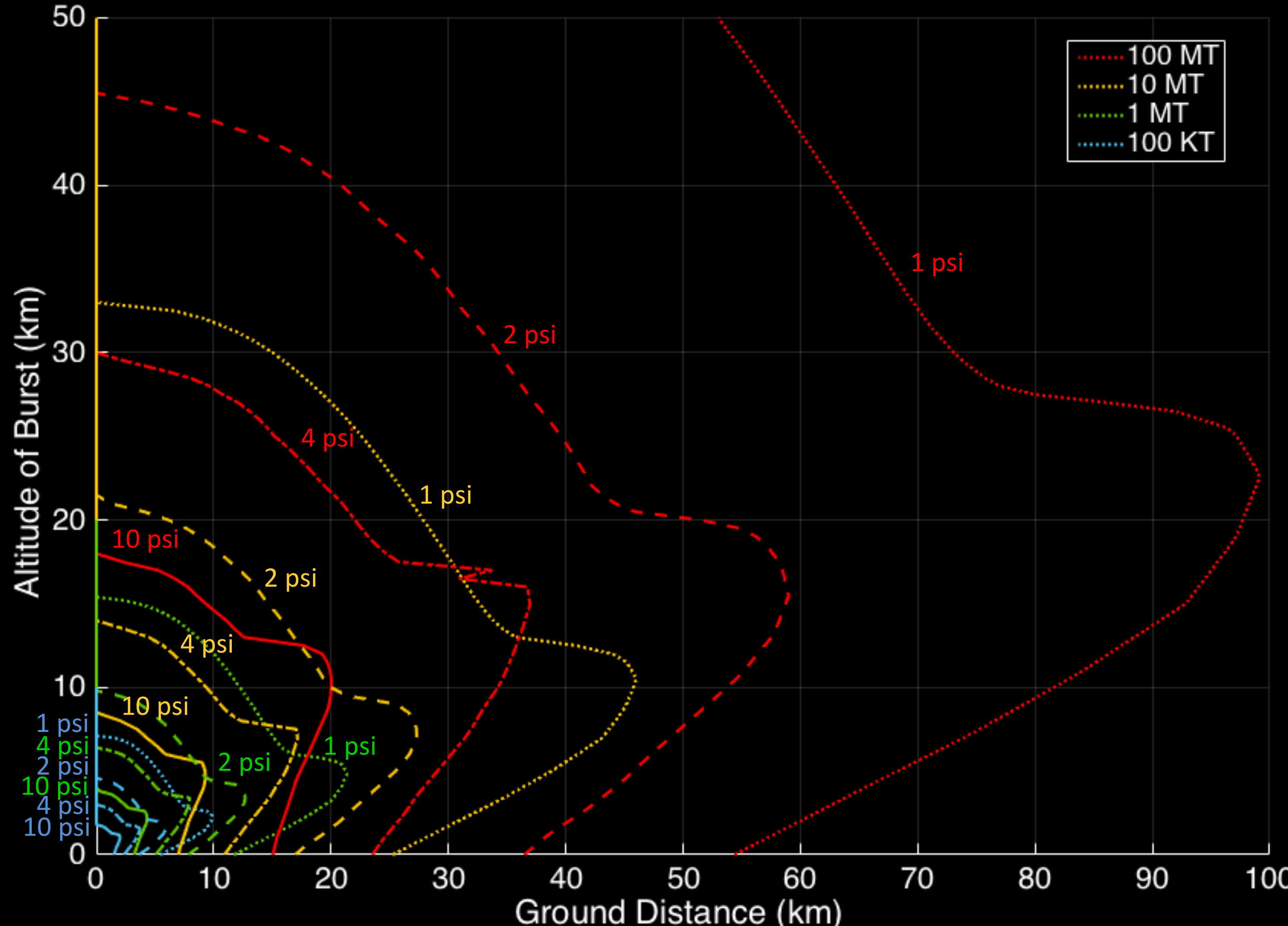


Chelyabinsk Observed Light Curve
σ=0.1MPa α=20° ⊘100m v=20km/s ρ=2g/cc
σ=1MPa α=20° ⊘100m v=20km/s ρ=2g/cc
σ=10MPa α=20° ⊘100m v=20km/s ρ=2g/cc
σ=0.1MPa α=90° ⊘100m v=20km/s ρ=2g/cc
σ=1MPa α=90° ⊘100m v=20km/s ρ=2g/cc
σ=10MPa α=90° ⊘100m v=20km/s ρ=2g/cc
Altitude (km)
0
10
20
30
40
50
60
Energy Deposition Rate (MT km^{-1})
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}

Density

Blast Radii

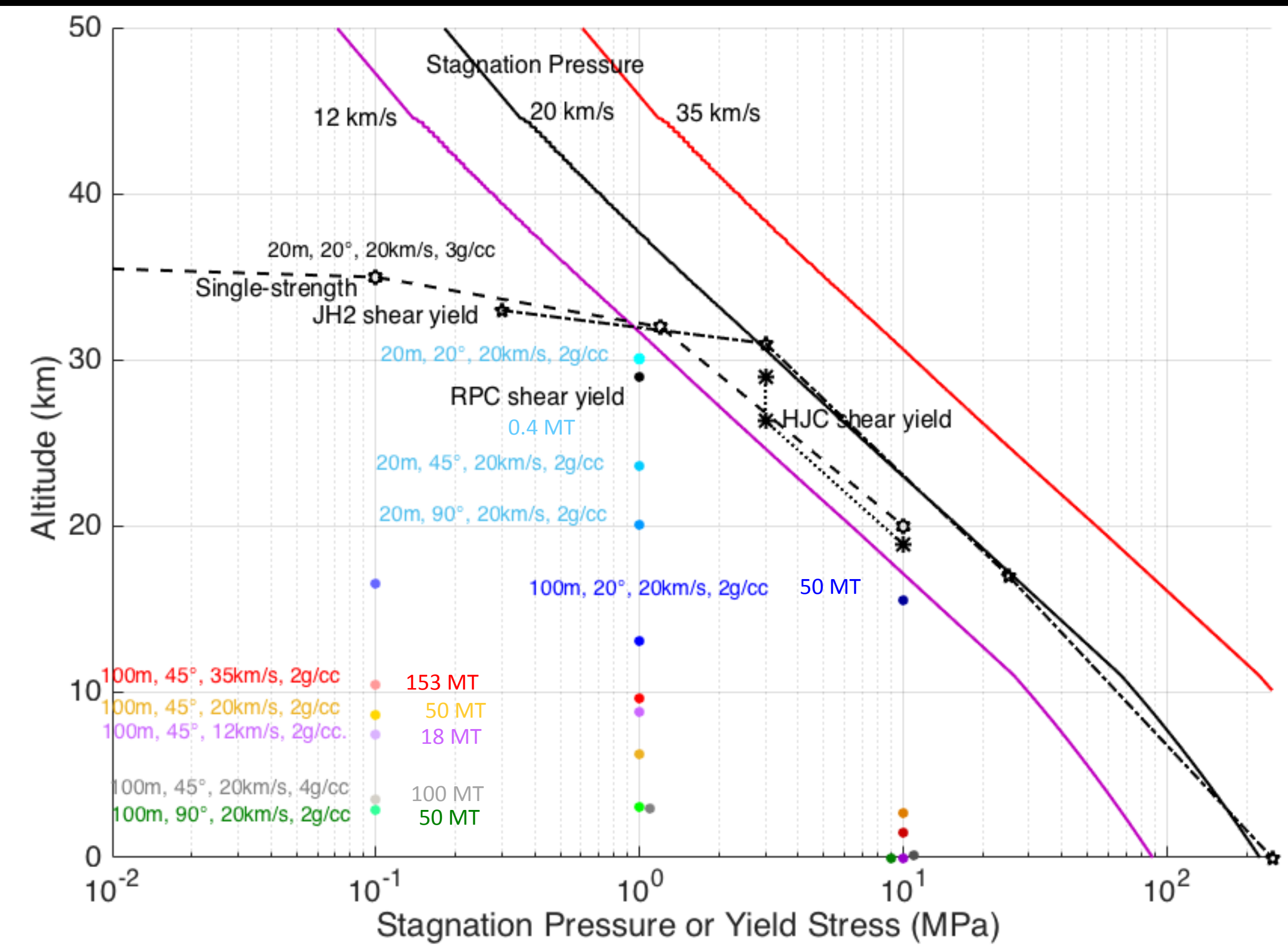
Glasstone & Dolan, 1977 – The Effects of Nuclear Weapons



- 10 psi (70% overpressure)
  Most buildings collapse
  99% fatalities
- 4 psi (30% overpressure)
  50% expected fatalities
- 2 psi (15% overpressure)
- 1 psi (7% overpressure)
  90% windows broken.
  Minimal fatalities

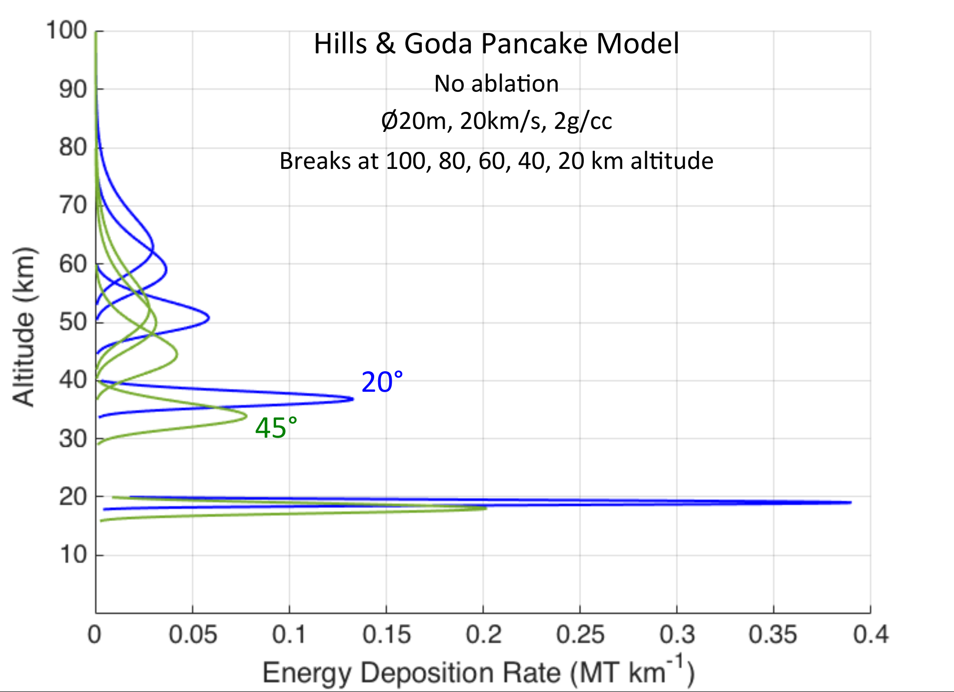
Caveat: Airbursts more like line charges and overpressures may decay significantly slower than predicted here.

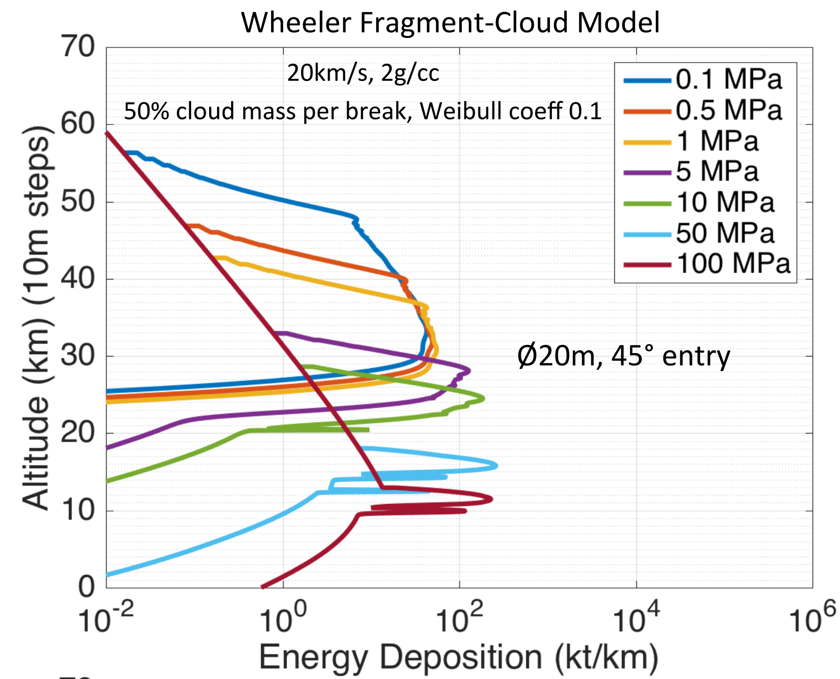
Airburst Altitude vs. Strength

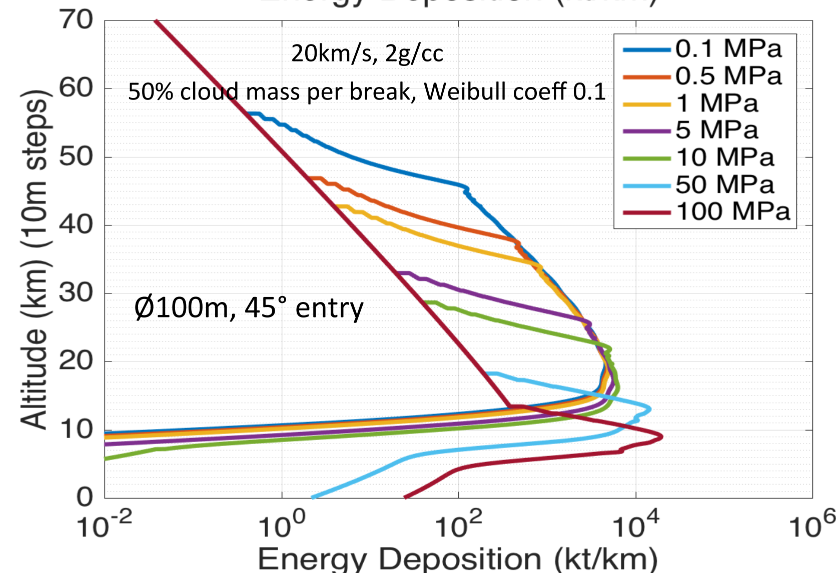


- Strong asteroids burst very quickly after stagnation pressure exceeds shear yield stress since pressures sufficient to rapidly disperse rubble
- Weak asteroids travel as a unit long after failed until pressures sufficient for disruption and all fail at similar heights (other parameters being the same)
- Ø100m asteroids for α>45° burst below 10km. Parameters will have little effect on ground damage.
- Ø100m shallow entries (<20°) can raise the burst altitude sufficiently to attenuate the worst of the effects (area>4psi) unless exceptionally strong
- Most Ø20m asteroids will burst above 20km and will likely cause minimal ground damage
- Ø20m asteroids more likely to be monolithic and strong enough (>10MPa) to burst below 20km where can great significant ground damage

Analytical Models







- Pancake model shows increasing rapidity of break-up with decreasing failure altitude, but weak asteroids still bursting much higher than hydrocode simulations
- Fragment-Cloud model shows peak energy deposition for weak asteroids all at similar altitude
- FCM model currently predicts slightly higher burst altitudes than hydrocode simulations